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Chapter 19

Injection and Beam Dump Systems

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Some of the elements of the LHC injection and extraction systems will be upgraded or replaced to adapt to the increased beam brightness and intensity of the HL-LHC beams [1; 2]. The injection main protection absorber will be replaced with new hardware which will be able to absorb and withstand **288 HL-LHC bunches** in case of an injection kicker failure. The compatibility with injection of 320 bunches (four batches of 80 HL-LHC bunches [3]) was also verified. One auxiliary injection protection collimator in Point 2 will be displaced closer to the interaction point (IP) to increase the acceptance of the ALICE Zero-Degree Calorimeter. The injection kickers, which suffered already from electron cloud, degraded vacuum and beam induced heating while operating with LHC beams, will be upgraded with several modifications to mitigate these effects. The compatibility of the LHC beam dump system with the increased beam intensities of the HL-LHC beams still needs to be fully assessed. However, the dump protection devices, as well as the dump absorber block and its entrance and exit windows needs an upgrade or replacement. The studies include the definition of the possible worst failure scenarios for the extraction and dilution kickers and the consequences on the different dump elements. Finally, the extraction and dilution system

will be upgraded to improve its reliability by reducing the risk of erratics, monitoring the status of the system and reacting faster in case of failures.

1. The LHC Injection System

The present layout of the LHC injection region, in the IR2 straight section, and the associated protection devices is shown schematically in Figure 1, an equivalent sequence of elements exists in IR8.

The beam to be injected passes through five horizontally deflecting steel septum magnets (MSI) and receives a total kick of 12 mrad. Four vertically deflecting kickers (MKI) merge the beam on to the LHC closed orbit by applying a total kick strength of 0.85 mrad. Uncontrolled beam losses resulting from MKI errors (missing pulses, erratic, partial, badly synchronized, or wrong kick strength) could result in serious damage to the downstream equipment. In particular the superconducting separation dipole D1, the triplet quadrupole magnets near the ALICE and LHCb experiments or the magnets in the arcs of the LHC machine itself could be directly hit by the beam. Also particle showers, generated by proton losses, could damage components of the detectors which are close to the beam pipe. Precautions must therefore be taken against damage and magnet quenches and collimators and beam absorber are placed at key locations in the injection regions.

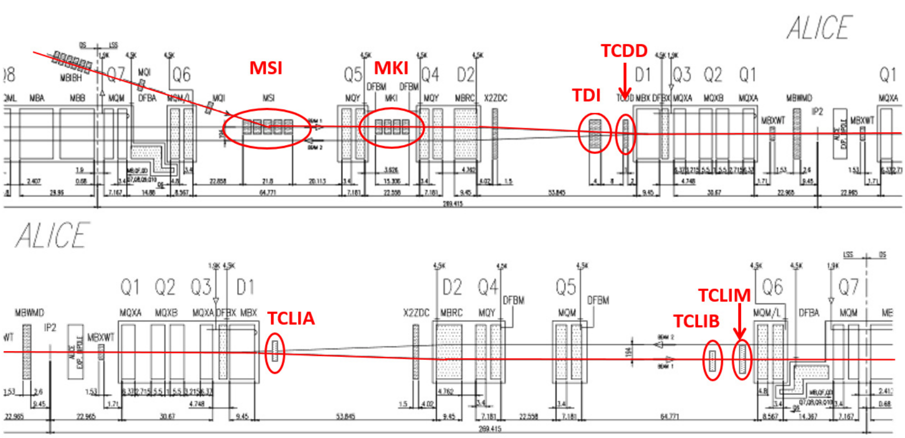

Fig. 1. Overview of the present injection system into the LHC and the associated protection devices (Beam 1, IR2). The beam is injected from the left hand side.

1.1. *Upgrade of the Injection Beam Absorber TDIS*

The present TDI is a movable two-sided vertical absorber which is installed at about 90° betatron phase advance from the injection kicker. Its main purpose is to protect machine elements in case of MKI malfunctions and timing errors.

The jaws of the TDIs presently installed in the LHC are 4.185 m long and accommodate blocks of graphite (6×47.1 cm), aluminium (1×60 cm) and $CuCr_1Zr$ (1×70 cm). The two latter blocks are retracted by 2 mm with respect to the graphite to avoid direct beam impact on these materials, which could lead to an excessive heating and stresses of these blocks. During the first years of the LHC operation, the TDIs in both IR2 and IR8 injection insertions were affected by several anomalies including outgassing, vacuum spikes, structural damage of the beam screens and elastic deformation of the jaws due to beam induced RF heating during the fills. Several hardware changes were already applied during the first long shutdown (LS1) and the following winter stops to mitigate the encountered problems [4]. Despite a visible reduction of the beam induced jaw deformation and of the vacuum activity, it was decided to develop a new improved design in terms of mechanics, robustness, reliability, setup accuracy, impedance and operational aspects in view of operation with higher intensity and brightness beams after LS2 [5].

Instead of having one long jaw, the new TDI (called TDIS, where the "S" stands for Segmented) will comprise three shorter absorbers (~1.6 m each) accommodated in separate tanks (see Figure 2 and Figure 3). The jaws of each module will all be identical except for the active absorber material. For robustness reasons, the two upstream modules will accommodate low-Z graphite absorber blocks (SIGRAFINE® R7550, 1.83 g/cm^3). The third module is foreseen to host higher-Z absorber materials (Ti_6Al_4V and $CuCr_1Zr$) to partially absorb and efficiently attenuate the particle showers from the low density upstream blocks.

The correct positioning of the TDIS jaws around the beam is vital for machine protection. Each module will be independently movable and redundant position measurements will be performed and checked via the Beam Interlock and the Beam Energy Tracking (BETS [6]) systems. The jaws of the third module will be slightly retracted compared to the upstream jaws to avoid direct beam impact on the higher-Z absorber blocks.

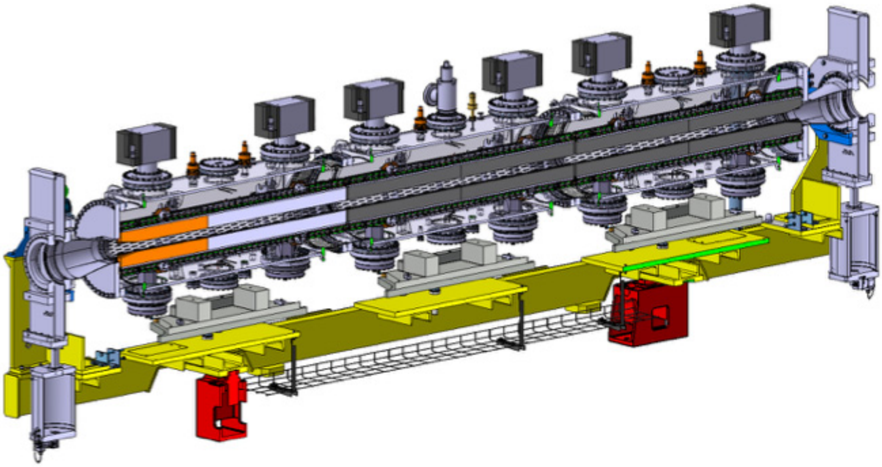

Fig. 2. The longitudinal cross section of the new TDIS showing the modules composed by different materials. The first two module jaws, starting from the right side of the figure, are made of graphite R7550 (dark grey), the last module is made of Ti_6Al_4V (light grey) and $CuCr_1Zr$ (orange).

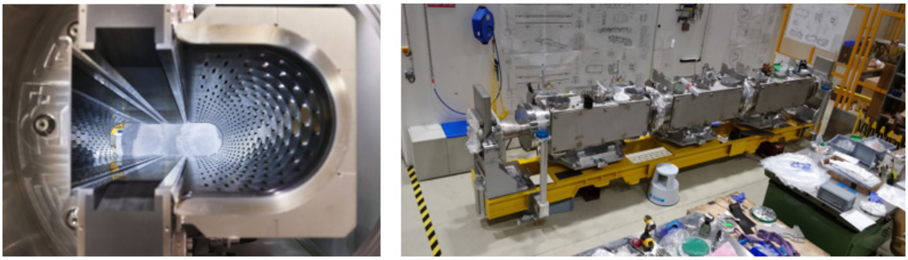

Fig. 3. Front view of the open tank of the first TDIS module (left) and side view of the three modules installed on the common girder (right).

1.2. *Supplementary Shielding of D1 Coils*

The superconducting D1 separation dipole is located just downstream of the TDIS. The largest energy deposition in the D1 coils can be expected if bunches impact close to the edge of the leading TDIS absorber block since secondary particle showers can escape through the TDIS gap. During the design of the present TDI, it was found necessary to add a complementary mask (TCDD in IR2 and TCDDM in IR8) in order to prevent damage to the D1 coils for such accident scenarios, see Figure 1. Detailed particle shower simulations [7] and damage tests at room and cryogenic temperature on NbTi cables, were carried out to determine if the efficacy of this protection system needs to be improved for HL-LHC beams. It was assessed that, in case of small beam impact parameters or grazing, the D1 magnet would certainly quench while no damage is expected. The most efficient way to further reduce the energy deposition on D1, and possibly reduce the risk of quench, consists in installing additional mask-like stainless-steel protection elements directly inside the insulation vacuum of the D1 cryostat (Figure 4). This solution offers the advantage of intercepting shower particles closer to the magnet without affecting the present machine aperture.

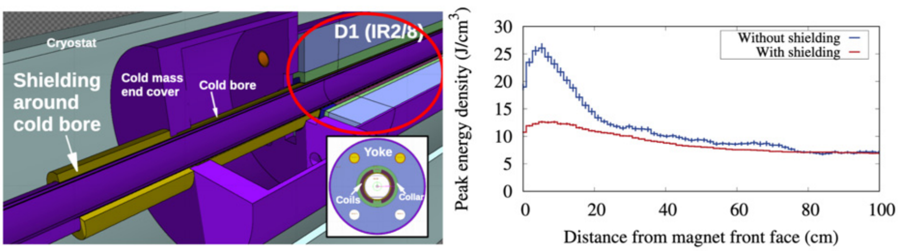

Fig. 4. 3D model of D1 cryostat where the additional shielding is installed around the cold bore to reduce the energy deposition on the magnet coils in case of injection failure (left). The expected reduction in the peak energy is also shown (right).

1.3. *Displacement of Auxiliary Injection Protection Collimator TCLIA*

The TCLIA is an auxiliary collimator which provides additional protection from mis-kicked beam in case of MKI failures. This device is set at an aperture of ±6.8 σ (using the nominal LHC emittance of 3.5 mm mrad for the calculation of σ) during the injection process. Once the injection is completed and the MKIs are in standby, the TCLIA is opened to parking position in order not to represent anymore an aperture bottleneck. The maximum aperture at parking position for the TCLIA is ±28 mm. This and its longitudinal position in IR2 have an impact on the acceptance of the Zero-Degree-Calorimeter (ZDC) of ALICE [8] which is a key detector used in heavy-ion operation to measure spectator neutrons and hence, the centrality of the collisions. For a given crossing angle, the ZDC is moved such that the straight-line prolongation

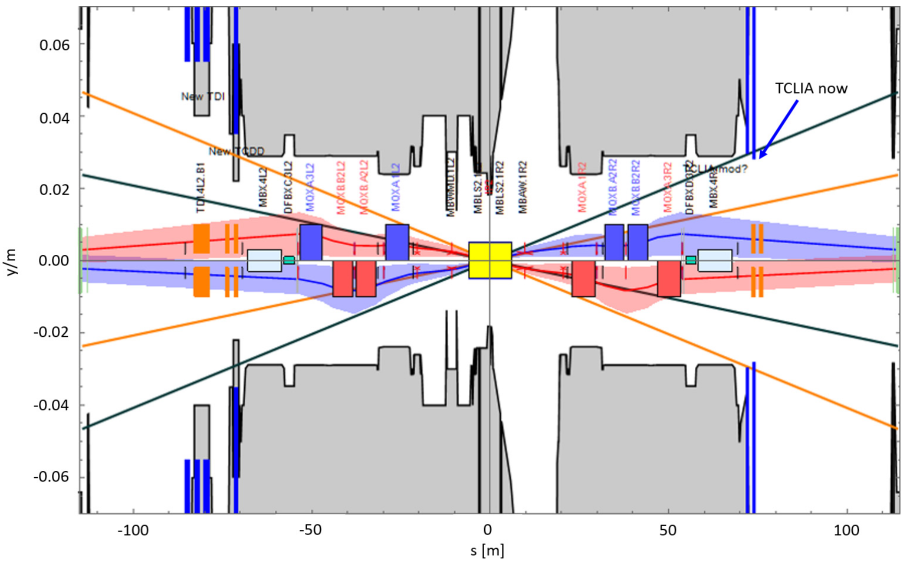

Fig. 5. IR2 aperture layout and 100 μrad neutron cone from IP2. The present TCLIA, even when fully opened to parking, is in the line of sight of the ZDC.

from the beam at the IP passes through the centre of the ZDC. The TCLIA on the right-hand side of IP2 protrudes into this line of sight, thus shadowing the ZDC, and poses a limit on the maximum allowed crossing angle as shown in Figure 5. The present configuration limits the maximum crossing angle to $\leq 60\ \mu$rad which is not compatible with operation with 50 ns bunch spacing (i.e. the present baseline for HL-LHC Pb−Pb physics) where an angle $\geq 100\ \mu$rad is needed. Studies were performed and it was found that the maximum TCLIA opening can be increased by 3 mm, without modifying the design, by pushing the setting of the mechanical end-stops and the related end-of-stroke switches to its physical limits. Moreover, the collimator will approach the IP by 2.2 m. These modifications will allow to achieve a crossing angle of 102.4 μrad compatible with the 50 ns Pb−Pb operation foreseen for the HL-LHC Pb-Pb exploitation.

1.4. *Upgrade of the Injection Kickers MKIs*

The injection kicker magnets are transmission line type magnets, each with 33 cells consisting of a U-core ferrite between two high voltage (HV) conducting plates [9]. With high bunch intensity and short bunch lengths, integrated over many hours of a physics fill, the real part of the beam coupling impedance of the magnet's ferrite yoke can lead to significant beam induced heating. To limit the longitudinal beam coupling impedance, while allowing a fast magnetic field rise-time, an extruded ceramic tube (99.7% alumina) with up to 24 screen conductors lodged in its inner wall is placed within the aperture of each MKI magnet. A set of toroidal ferrite rings is mounted around each end of the alumina tubes, outside of the aperture of the magnet: the original purpose was to damp low-frequency resonances. To ensure reliable operation of the MKI magnets, the temperature of the ferrite yokes must not exceed their Curie point, which is ∼125°C for the ferrite used. At this temperature the magnetic properties of the ferrite are temporarily compromised and the beam cannot be injected.

Both the MKI kickers installed in IR2 and IR8 prior to LS1 encountered a number of issues which affected operation. These include beam-induced heating, electrical flashovers, beam losses and electron cloud related vacuum pressure rise [10].

Electron cloud in the ceramic tube results in a pressure rise, which can cause an electrical breakdown and surface flash-over, hence an interlock prevents injection when the pressure is above a predefined threshold. The conditioning process of the alumina tube with beam is slow, requiring approximately 300 hours [10], and this could strongly affect beam operation in particular in case of replacement of a magnet in the middle of a run. Studies and measurements showed that a low SEY coating could mitigate multipactoring, and thus the related pressure rise, permitting more reliable operation of the injection kickers. A prototype MKI, with a 50 nm thick Cr_2O_3 coating applied by magnetron sputtering to the inner part of the alumina tube, was installed in IR8 during the winter stop between 2017 and 2018 [11]. A rapid reduction of the dynamic vacuum and faster conditioning, with respect to the original design, was observed during the scrubbing run and in operation. In addition, the Cr_2O_3 coating has not resulted in a statistically significant change in the number of UFOs (macro particles falling into the beam). The beam screen of all the MKIs was upgraded during LS1 to allow the full complement of 24 screen conductors to be installed. The modified design allowed the surface flashover rate to be further reduced [9]. The post-LS1 design also resulted in a considerable reduction of beam induced power deposition in the ferrite yoke [12] and no limitation was encountered in operation during Run 2 [13]. A further reduction in the yoke temperature was observed in the IR8 prototype where the beam screen was modified to reduce the total power loss and move the main losses from the yoke to the ferrite rings [14]. Thermal simulations were carried out to confirm that the calculated power losses for Run 2 agreed with the temperatures measured during LHC operation. A good agreement was found and no issues were foreseen since a maximum temperature of 110°C was calculated in the first cell at the upstream end of the upgraded magnet [13]. However, for operation with HL-LHC type beams, the power deposition in the MKI is expected to be a factor of four greater than for LHC, which would be unacceptably high with the existing design [15]. Studies showed that, following the redistribution of power from the yoke to the ferrite rings, an active water cooling system just of the ferrite rings is sufficient to keep the temperature of the full magnet well below 100°C also for HL-LHC beams [16]. A complete prototype with Cr_2O_3 coated chambers, upgraded beam screen with active cooling of the ferrite rings, the so called "MKI cool" (Figure 6 [10]),

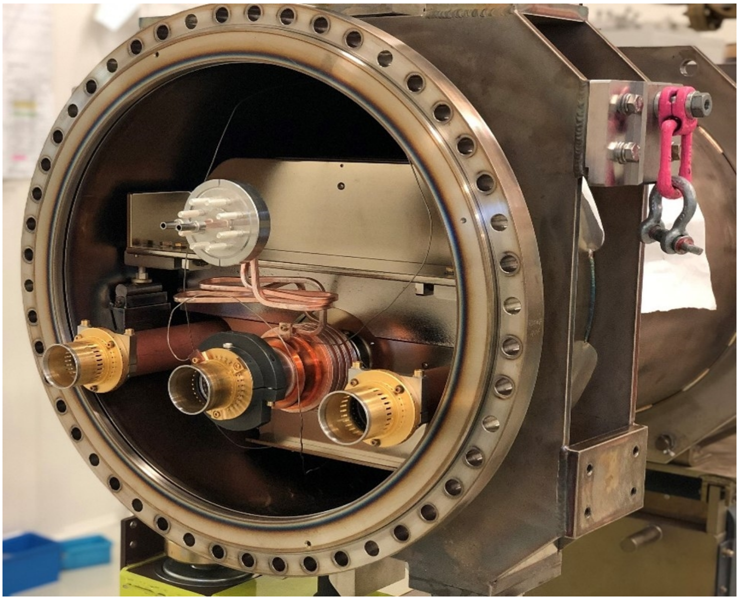

Fig. 6. Front view of the upgraded MKI-cool with the newly designed beam screen and cooling system of the ferrite cylinder.

will be installed and tested in the LHC for the final validation before launching the upgrade of the full MKI series.

2. The LHC Beam Dump System LBDS

The beam is extracted from the LHC, by means of fifteen pulsed extraction kickers (MKD) and DC septum magnets (MSD) located in a dedicated insertion of the LHC (IR6, schematic view in Figure 7 for Beam1 - the layout for Beam2 is mirror symmetric), towards a long drift chamber and a graphite absorber dump block (TDE). A system of four horizontal (MKBH) and six vertical (MKBV) dilution kickers is powered with anti-phase sinusoidal currents to sweep the beam over the front face of the TDE in order to reduce the deposited energy density. To avoid losses during the rise time of the LHC MKD, a 3 μs long abort gap in the circulating bunch pattern is kept free of particles. So-called asynchronous beam dumps can be caused by loss of synchronisation of the MKD rise time with the abort gap, e.g. in case of failure of the Trigger Synchronisation Unit (TSU), or by the erratic pre-firing of an extraction kicker. In these cases, the beam can be swept over the machine aperture and dedicated absorber blocks are installed in the LHC extraction region to protect the down-stream elements.

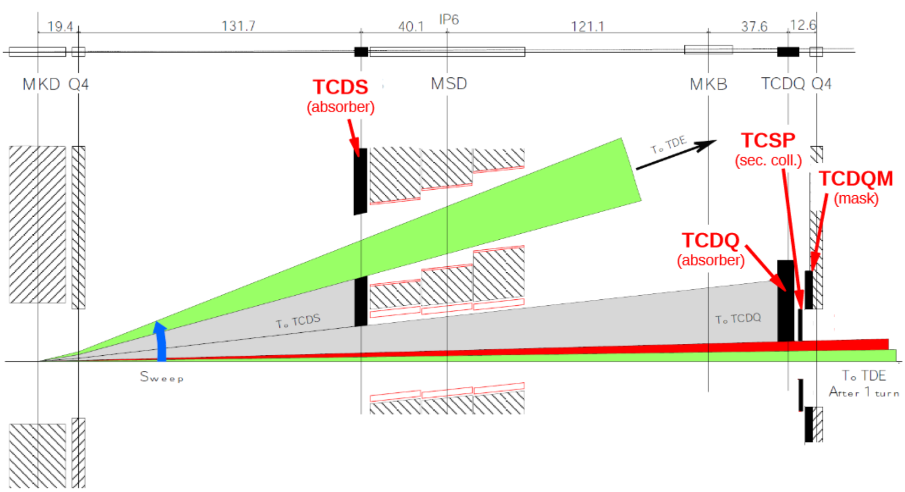

Fig. 7. Overview of the LHC extraction region (Point 6).

2.1. *Beam Dump System Absorbers TCDQ and TCDS*

Several failure modes exist in the synchronization system and in the kicker switches that could lead to an asynchronous dump where part of the beam would be swept across the LHC aperture. Without dedicated protection devices this would lead to massive damages. The protection devices against asynchronous beam dump damages are: the TCDS, which is a fixed absorber that directly protects the downstream extraction septum MSD and the TCDQ, which is a movable absorber that protects the superconducting quadrupole Q4 and further downstream elements, including the arc and the tertiary collimators (TCTs) around the experiments. A secondary collimator with embedded beam position monitors (TCSP) is installed right after the TCDQ and allows an accurate measure of the beam center position while providing further cleaning. A fixed mask (TCDQM) is installed right upstream of Q4 to intercept secondary particle showers and thus reduce the energy deposition in the superconducting coils. The TCDQ was already upgraded in LS1. The new design, which is described in detail in [17], includes an extension of the absorber length from 6 m to 9 m, and the replacement of the higher density graphite absorber material with different grades (1.4 g/cm^3 and 1.8 g/cm^3) of carbon fibre composites (CfC). This design was supposed to be compatible with operation with HL-LHC beams. During the reliability runs performed in 2015 a new type of MKD erratic firing (Type 2), with a different rise time than the standard one (Type 1), was identified. This case is more critical since a higher number of bunches can impact the TCDQ with a large density close to the jaw surface (see Figure 8). New studies were carried out to verify the robustness of the TCDQ also for this new failure scenario [18]. Depending on the optics, the TCDQ jaw will have to be set at an aperture which could vary between 2.5 mm and 3.9 mm. No damage is expected if the TCDQ sits at $\geq$3 mm from the beam while, for smaller gaps, the peak dose could go above 2.7 kJ/g (Figure 8) corresponding to a temperature $\geq$1500 C. The present knowledge of the material properties at such temperature is quite poor and does not allow to exclude possible failures. Further TCDQ upgrade is not part of the HL-LHC baseline and presently, alternative mitigations (i.e. Type 2 erratic prevention, improved monitoring of the local orbit, suitable optics conditions, etc.) are being evaluated.

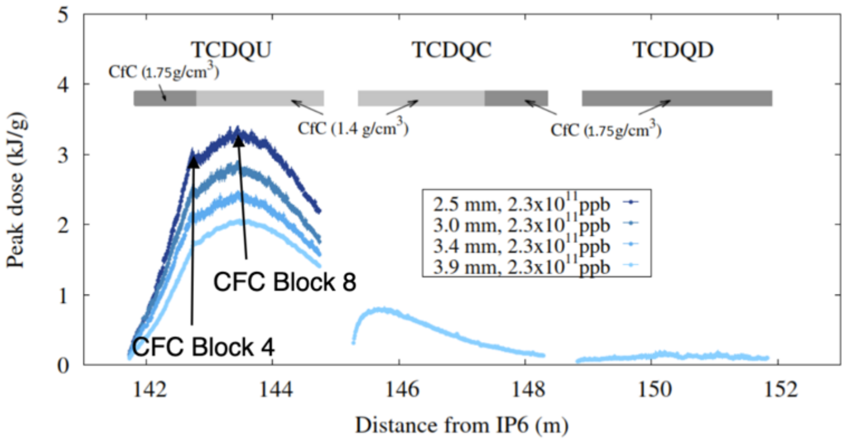

Fig. 8. Peak dose along the TCDQ modules in case of asynchronous beam dump with the TCDQ sitting at different apertures depending on the optics requirements.

The Beam Energy Tracking System (BETS [19]) monitors the position of the TCDQ as a function of the beam energy. This HW interlock was implemented in LS1 to have a redundant check of the TCDQ positioning in case of failure of the standard control system. This forbids moving the TCDQ outside pre-defined thresholds at fixed energy and might be a limitation for the ATS optics when the β-function at the TCDQ changes during the squeeze and the protection element should vary its position accordingly. In case this affects the HL-LHC β^* reach, the BETS should be upgraded to allow for TCDQ movements during the squeeze. This activity is not part of the present baseline.

The robustness of the TCDS and the protection of the MSD magnets, in case of an asynchronous beam dump with full intensity HL-LHC beams, was verified for all types of erratics [18]. A maximum energy density of 2.5 kJ/cm^3 (∼1150 °C) was calculated in the low-density blocks (graphite and CFC) and of ≥1 kJ/cm^3 in the Ti block. Thermo-mechanical studies indicate that the Ti block will experience plastic deformation and some low-Z blocks could fail due to the high stresses and elevated temperatures reached. The calculated energy deposition at the first downstream MSD septum corresponds to a temperature increase of less than 100 K (∼130 °C absolute temperature). This temperature is not critical concerning possible changes in the magnetic properties of the steel (up to 150 °C is considered acceptable). Moreover the peak temperature is reached in a peripheral part of the yoke so that no issue is expected for the insulation of the coils. Further studies are needed to evaluate if a temperature increase of up to 100 K could induce a deformation of the vacuum chamber of the circulating beam. Moreover FLUKA and ANSYS calculations have to be performed to quantify the temperature increase of the water in the MSD cooling pipes and thus evaluate the pressure rise and the consequent risk of shock-waves. The TCDS upgrade with an additional 3 m long module in front of the existing ones is included in the HL-LHC baseline.

2.2. *The Beam Dump TDE*

The LHC beam dump consist of an upstream window made of carbon-carbon composite on a thin stainless steel foil, a ~8 m long graphite dump core, a downstream Ti window and is kept under N_2 gas at higher than atmospheric pressure. The TDE and its entrance and exit windows will need to withstand the repeated dumps of high intensity HL-LHC beams. Simulation studies show that, in case of a regular dump of HL-LHC beams a peak temperature of ∼1800 °C (a factor ∼2 higher than for the LHC beams) will be reached in the core. In case of failure of the dilution kickers, the sweep pattern is altered (Figure 9) and significantly higher temperature and stresses can be reached.

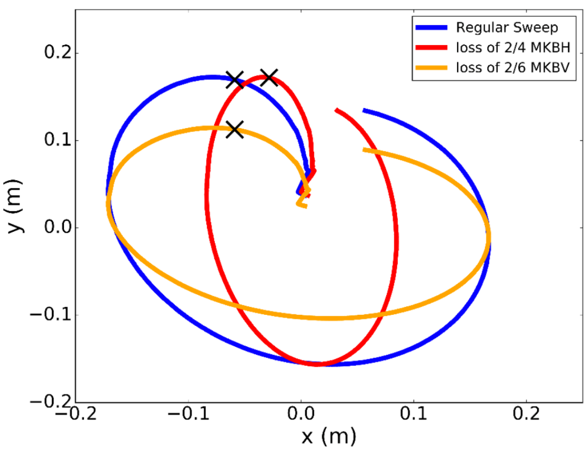

Fig. 9. Simulated beam sweep patterns at the dump for a regular sweep (blue) and the failure cases of 2 out of 4 horizontal (red) and 2 out of 6 vertical dilution kickers missing (orange). The positions of highest energy deposition are marked with a black cross.

The originally assumed worst failure scenario was the loss of two MKBs due to either the erratic firing of one kicker and perfect phase opposition with the remaining ones or a flashover simultaneously affecting two MKBs sharing the same vacuum tank. In addition, due to the smaller number of horizontal modules, their contribution in case of a failure is more critical and, for the given dilution pattern, the system is more sensitive to the loss of horizontal dilution. In case of two missing horizontal MKBs, the peak temperature can go up to 2800 °C. No information is available about the core material behavior at this temperature and mechanical characterisation studies are being performed to evaluate if any modification of the present design is needed.

The expected stress level at the present windows, also in nominal operational conditions, would be too high to insure a long term and reliable operation with HL-LHC beams [21]. For this reason they will be upgraded to ensure their survival also in case of dumps with two missing MKBs.

Moreover, during Run 2, a series of N_2 leaks appeared at the flange connections and were ascribed to large vibrations of the whole dump due to beam energy transfer during high intensity dumps. This required periodical interventions to tighten the flanges and a new nitrogen line with surface supply was built to be able to maintain the dump at the required over-pressure. Possible solutions to vibrations are being evaluated since the problem will be worsen when operating with higher intensity beams.

No dump upgrade was originally included in the HL-LHC baseline since detailed studies, identifying weaknesses and defining needed modifications, were missing. Presently, clear indications of possible limitations and required upgrades are available but key aspects, like the mechanical behavior of the core material and how to address the problem of the vibrations, are still being investigated. The goal is to having all the information to be able to define the complete upgrade strategy by 2021 in order to be ready for installation in LS3. The HL-LHC project committed to upgrade the dump with the help of the Russian in-kind contribution.

2.3. *LBDS Kickers, Generators and Control System*

During reliability runs, tests and operation with beam of the LBDS kickers a number of erratic triggers due to electric breakdowns and unexpected failures were encountered.

The breakdowns were located at regions with large electrical fields of around 3 MV/m at the edges of the insulators in the generators. Replacing the critical insulators and cleaning the critical areas in the generator allowed a reliable operation of the MKD system at 6.5 TeV. However, operational margins are considered too small for long-term reliable operation at 7.0 TeV for HL-LHC. For this reason a redesign of the switch stacks of the MKD generators is ongoing with the aim of keeping the electrical field below 1.5 MV/m in all areas. The replacement of the generator switch stacks is foreseen for LS2. Simultaneously, the power triggering and re-triggering system of the MKD switches will be upgraded [23]. The power triggers are presently rated at a current of 500 A and a dI/dt of 400 A/μs for a voltage of 3.5 kV. The upgraded system will double the current and almost double the dI/dt for a reduced voltage of 3.0 kV. The new parameters are better in line with the specifications of the manufacturer and will increase the lifetime of the GTO switches, will result in a shorter rise time and will make the power trigger less sensitive to radiation. The re-trigger system triggers all the extraction and dilution kickers as quickly as possible in case of an erratic closing of an extraction kicker switch. The present re-trigger delay is about 900 ns and the aim is to try to reduce it even further to minimise the load on the TCDQ and the ring elements, in particular the tertiary collimators, in case of an asynchronous dump. Also the diagnostic tool (IPOC) will be upgraded and a sparking activity surveillance system will be implemented to monitor the status of the generators, allow reacting in case of signs of nonconformity and provide statistics for a better understanding of the correlation between sparks and erratics. At the same time the electronics of the re-triggering system, which is becoming obsolete, will be replaced.

Beside Type 2 erratics for the MKDs, unexpected failures affected also the dilution kickers. In particular, the parasitic electromagnetic coupling, through the re-triggering line, caused the firing of neighboring MKB generators [22]. This event, combined with anti-phase could determine the loss of more than two MKBs, which was identified as the worst failure scenario in the original design of the system. Moreover, up to three MKBVs were lost, at one occasion, due to a flash-over propagation with some delay and anti-phase in two kickers sharing the same vacuum tank [24]. All these cases might have dramatic effects on the beam dump when operating with HL-LHC beams, in particular in case of MKBH failures. Different upgrade scenarios for the dilution system are being considered [25]. The MKBH generators will be upgraded to reduce their operational voltage (presently higher than the MKBV voltage due to the lower number of MKBHs). A new re-triggering system for all the MKBs will be put in place to eliminate the risk of anti-phase in case of erratics. Different sweep patterns are then expected at the dump depending on the delay between the erratic and the execution of a synchronous dump as shown in Figure 10. The consequent energy deposition on the dump windows and the core are being evaluated for all possible relative delays. Finally, it is proposed to install two additional MKBHs per beam since this is the only fully reliable solution to reduce the risk and the sensitivity to any possible failure and open the possibility to increase the nominal sweep pattern to reduce the stresses on the dump also during nominal operation. The HL-LHC project has approved the upgrade, and implemented it in the baseline through the Russian in-kind contribution. The installation is foreseen for LS3.

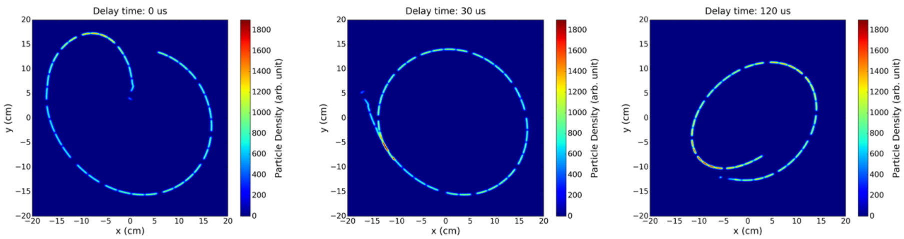

Fig. 10. Simulated sweep patterns in case of MKB re-triggering for different delays between the erratic event and the synchronous dump execution.

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